DESIGN AND DEMONSTRATION OF MMW RADAR FOR DEDICATED BIRD DETECTION AT AIRPORTS AND AIRFIELDS

Lawrence A. Klein, Ph.D.[1], Michel Hovan, Ph.D.[2], Gerard Genello[3], and Paul Antonik[4]
[1]WaveBand, Corp., 17152 Armstrong Avenue, Irvine, CA, 92614, USA
[2]Federal Aviation Administration, W.J. Hughes Technical Center, AAR-410, Bldg. 296, Atlantic City International Airport, NJ 08405, USA
[3,4]U.S. Air Force Research Laboratory/SNRT, 26 Electronic Parkway, Rome, NY 13441 USA
[1]Tel: + 949 253 4019, Fax: + 949 253 4089, Email: lklein@waveband.com
[2]Tel: + 609 485 5552, Fax: + 609 485 4845, Email: michel.hovan@tc.faa.gov
[3]Tel: + 315 330 3576, Fax: + 315 330 2528, Email: genellog@rl.af.mil
[4]Tel: + 315 330 7057, Fax: + 315 330 2528, Email: paul.antonik@rl.af.mil

Abstract

A 94 GHz millimeter-wave (MMW) radar has been designed, built, and demonstrated for dedicated bird detection at airports and airfields during aircraft final approach and departure. The radar classifies birds or bird flocks by their bio mass (assumed proportional to their radar cross section) and identifies the range, azimuth, and elevation position of the birds. The maximum operating range is approximately 3 miles (4.8 km). Radar cost is low, in part due to the use of a unique antenna that scans without gimbals or phased array components. The radar design is based on analyses that explored operating frequency trades (i.e., available power sources, spatial resolution, and atmospheric attenuation produced by rain) and detection range as a function of post processing time (i.e., integration time).

Deployment of the radar at a bird sanctuary in Southern California verified its ability to detect small birds, such as turns and gulls, and large birds, such as cormorants, pelicans and geese, at ranges compatible with the design goals. Additional tests were performed at the Air Force Research Laboratory at Rome, NY to calibrate the radar and at John F. Kennedy International Airport in New York to demonstrate the radar's performance in an operational environment. An extended deployment at the Dallas-Ft. Worth Airport is planned for Spring 2004.

This work was performed as part of the Dual-Use Science and Technology (DUST) Program under Agreement Number F30602-02-2-0119.

Key words: radar bird detection, MMW radar, bird detection, 94 GHz bird detection radars, airport bird detection, RF bird detection, runway bird detection.

1. Introduction

Bird detection at commercial and military airports is one of increasing urgency as bird populations increase and the numbers of encounters with aircraft subsequently increase. Bird-induced aircraft damage can be reduced by several measures, which include managing the local habitat so that airports do not attract bird populations, dispersing birds from the premises by active and passive devices, removing birds by moving or destroying nesting sites, and detecting bird activity by radar sensors with automatic reporting of any potentially hazardous events to air traffic controllers and pilots.

The radar described in this paper detects birds in the airspace surrounding airports and generates reports of any detected bird activity, which can be transmitted to air traffic controllers and pilots. The radar sensor utilizes a 94 GHz frequency-modulated, continuous wave (FMCW) signal source connected to a unique scanning antenna. The antenna beamwidth is 0.5-degree in one direction and 5 degrees in the orthogonal direction. In this particular design, the 0.5-degree beam is electronically scanned over 30 degrees. Other antenna designs enable electronic scanning over larger fields of view. The orthogonal direction is scanned using a stepper motor. The antenna can be mounted as shown in Figure 1 to enable narrow beamwidth scanning in the horizontal or azimuth direction, or on its side for narrow beamwidth scanning in the vertical or elevation direction depending on need. The entire radar, i.e., antenna, transmitter, and receiver, occupies a small volume and can be powered from a 12-Volt automotive battery using a 700 Watt DC to AC converter if portable or remote operation is required.

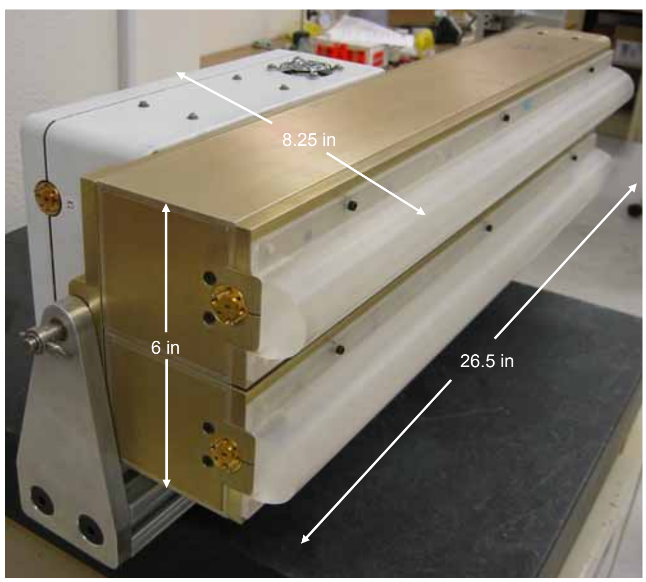

Figure 1. 94 GHz radar for bird detection at airports.

2. Radar performance requirements

The developmental requirements for the millimeter-wave radar are shown in Table 1.

Table 1. MMW radar operational considerations for bird detection.

Constraint	Description
Objective	Detect and track movement of bird species in and around airports
Altitude	Up to 3,000 ft (0.91 km) AGL in airport approach and departure corridors
Radar mounting height	Function of proximity to runway
Detection range	3 statute mi (4.8 km) minimum, 5 statute mi (8 km) desired (multiple radar units can be used) Post processing of raw data, such as integration of independent samples, can be used to increase signal-to-noise ratio and hence detection probability
Data latency	10 seconds for newest information to appear on display
Weather	Performance in rain based on attenuation expected from drizzle or light rain

Since the radar will normally be scanning the sky or atmosphere, the primary performance criterion is the signal-to-noise ratio (SNR) of the received signal. The SNR is derived from the equation for the power received by a radar, namely

$$P_r = \frac{P_t G_r G_t \sigma \lambda^2}{(4\pi)^3 R^4 L}, \tag{1}$$

where

P_r, P_t = received, transmitted power (W),
G_r, G_t = gain of receive, transmit antennas,
σ = radar cross section of target (m^2),
λ = wavelength of transmitted energy (m),
R = range to target (m).
L = sum of losses (MMW hardware insertion losses + antenna ohmic losses + atmospheric losses).

The quantities in parentheses that follow the definition of the factors in the equation denote the measurement units.

The noise power generated in the radar receiver is given by

$$P_N = (290\text{K})\,(\text{NF})\, k_B\, B_{IF}, \tag{2}$$

where

P_N = noise power (W),

NF = single-sideband receiver noise figure,
k_B = Boltzmann's constant = 1.380662 x 10^{-23} J/K,
B_{IF} = intermediate frequency (IF) receiver bandwidth (Hz).

The raw SNR is found as (1) divided by (2) or

$$\text{Raw SNR} = \frac{P_r}{P_N}. \tag{3}$$

The real-time SNR is equal to the raw SNR increased by the signal processing gain of the radar. The 94 GHz FMCW radar has 36 dB of signal processing gain contributed by the real part of a 8,192-point fast Fourier transform (FFT). Thus, the real-time SNR in dB is

$$\text{Real-time SNR}|_{\text{dB}} = 10 \log (\text{Raw SNR}) + \text{Real-time signal processing gain}|_{\text{dB}} \tag{4}$$

Signal-to-noise ratio and, hence, detection probability can be increased further by post processing using spatial integration over several range bins and temporal integration of return pulses over tens or hundreds of milliseconds. Figure 2 depicts the effect of temporal integration, which noncoherently integrates pulse returns. The results are based on a Swerling 2 fluctuating target (many independent rapidly fluctuating random scatterers, where no single scatterer is dominant) and a false alarm probability of 1.2 x 10^{-5}. Each curve shows the number of pulses required to be integrated to achieve the detection probability represented by the curve.

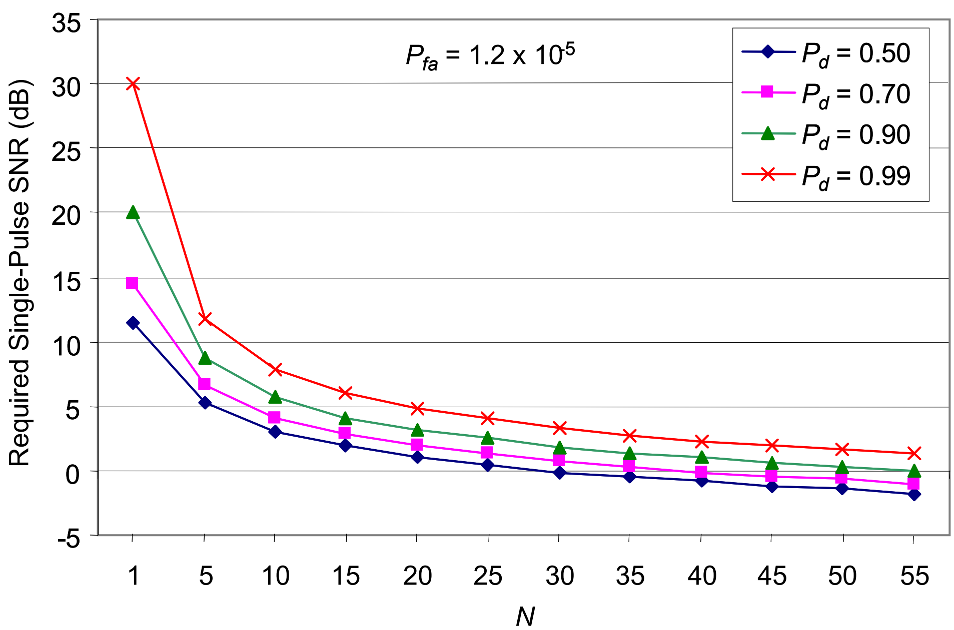

Figure 2. SNR as a function of the number of returns N noncoherently integrated for a Swerling 2 fluctuating target.

Thus, a single-pulse SNR = 20 dB is required to achieve a detection probability of 0.9 when only one return is used. However, when 15 returns are integrated, the single-pulse SNR requirement decreases to 4.1 dB.

3. Predicted radar detection probability performance

The specifications for the 94 GHz FMCW radar and operating scenario are given in Table 2.

Table 2. 94 GHz radar and target characteristics.

Parameter	**Value**
Center frequency	94.3 ± 0.5 GHz
Azimuth beamwidth	0.5 degree
Elevation beamwidth	5 degrees
Antenna gain (transmit and receive, each)	38 dB
Antenna polarization	Vertical (when narrow beamwidth scans azimuthally)
Antenna losses (one way)	Less than 3 dB
Azimuth scan field of view	30 degrees
Azimuth scan time function	Linear, true continuous
Azimuth scan speed	Up to 12 scans per second
Angles/frame	60 to 120
Elevation angle scan	30 degrees
Output power	575 mW CW
Noise figure	6 dB with low noise amplifier
IF bandwidth	5 MHz
RF modulation bandwidth	230 MHz
RF modulation period	1.6 ms
IF processing	8,192 FFT (4,096 utilized giving 36 dB processing gain)
IF dynamic range	82 dB
Displayed range cells	Up to 4,096 per azimuth beam
Range cell size	0.65 m
Target radar cross section	0.0015 m^2 for individual birds 0.03 m^2 for bird flocks
Rain attenuation	0.05 dB/km (one way) in drizzle 0.2 dB/km (one way) in light rain (1 mm/hr) 1.0 dB/km (one way) in moderate rain (4 mm/hr) (The moderate rain condition is for information only. It was not used in the modeling exercises.)

Figure 3 illustrates the SNR and detection probability for detecting individual birds and bird flocks with a 575 mW, 94 GHz radar, low noise amplifier, and post processing of 625 frames of range data integrated over a period of 1 s. The birds are modeled as a Swerling 2 fluctuating target. The effective range for detecting bird flocks in this scenario is approximately 3 mi (4.8 km). The target detection models in *Radar Target Detection: Handbook of Theory and Practice* by D.P. Meyer and H.A. Mayer (Academic Press, NY, 1973) were used to assist in these calculations.

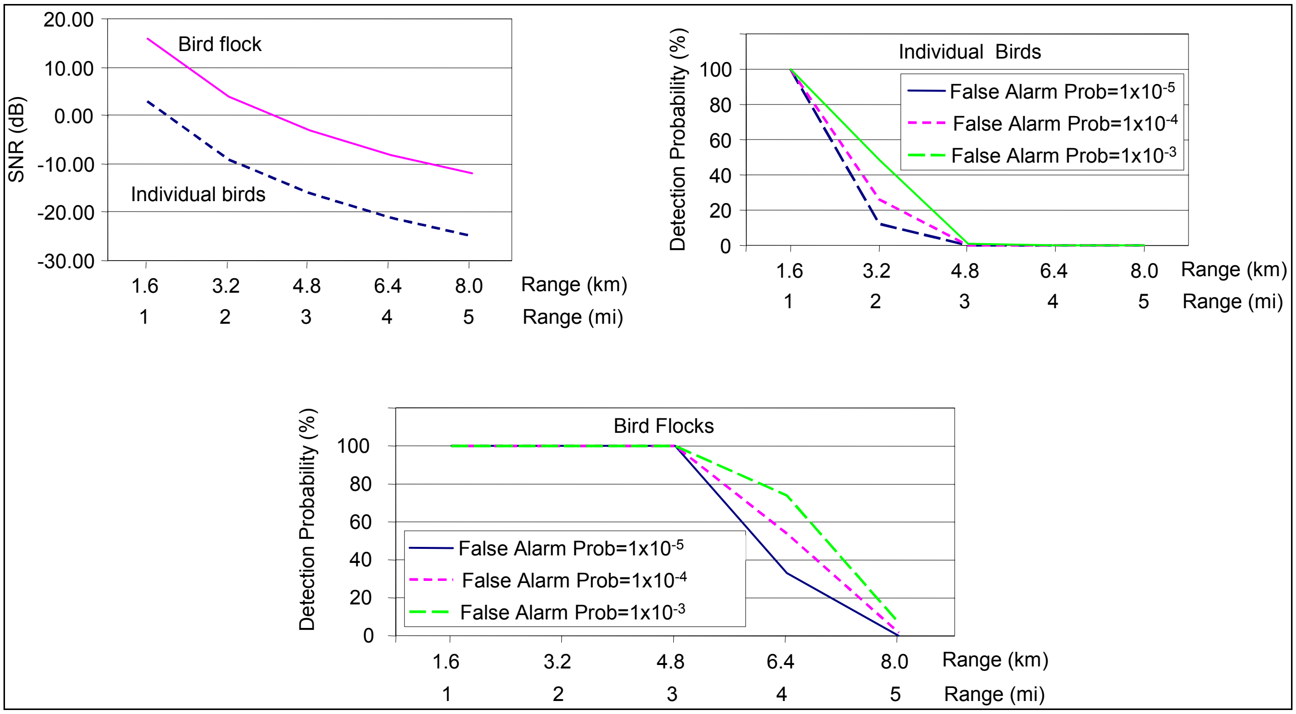

Figure 3. SNR and detection probability of individual birds and flocks versus range with a 575 mW, 94 GHz radar and post processing of 625 frames of range data in 1 s. Detection range for bird flocks is approximately 3 mi (4.8 km).

Table 3 summarizes the bird flock detection ranges and probabilities for several radar configurations as a function of transmitted power, weather conditions, and number of frames of range data integrated during post processing.

Table 3. Radar performance summary for detection of bird flocks.

Radar Configuration	**Weather**	**Frames Integrated[1]**	**Integration Time[1]**	**Effective Range (mi)**	**(km)**	**Detection Probability[2] (%)**
94 GHz, 575 mW	Nominal	100	160 ms	2	3.2	≈100
94 GHz, 575 mW	Nominal	625	1 s	3	4.8	≈100
94 GHz, 1 W	Nominal	100	160 ms	2 to 2½	3.2 to 4.0	60 to ≈100
94 GHz, 1 W	Nominal	460	736 ms	3	4.8	90 to ≈100

1. Assuming birds remain in detection area of radar for the required integration time.
2. Function of range and false alarm probability.

4. Antenna footprint

The geometry for the antenna footprint calculation is shown in Figure 4. Since the mission of the radar is to detect birds with good altitude resolution, the antenna is oriented such that the narrow beamwidth is in the vertical or height direction with horizontal polarization. The height footprint dimension h is given by

$$h = d\,[\tan(\theta + \theta_e/2) - \tan(\theta - \theta_e/2)] \tag{5}$$

and the azimuth footprint dimension AZ by

$$AZ = 2R\cos\theta\,\tan(\theta_a/2) = 2d\,\tan(\theta_a/2), \tag{6}$$

where

- d = $R\cos\theta$ = ground distance between radar and target (m),
- R = slant range from radar to target (m),
- θ = radar elevation viewing angle with respect to horizontal,
- θ_e, θ_a = elevation and azimuth 3-dB antenna beamwidths.

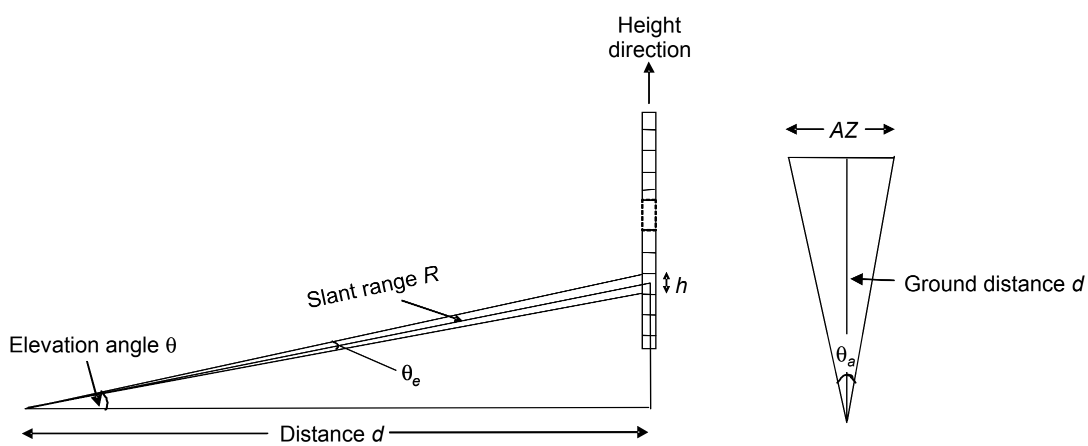

Figure 4. Radar antenna footprint geometry.

5. FMCW range calculation

Other radar design parameters that affect the detection range R of an FMCW radar are the radio frequency (RF) modulation bandwidth ΔF of the transmitted waveform and the RF modulation frequency f_m. They are related to range through

$$R = \frac{c f_{IF}}{2\,\Delta F f_m} = \frac{c\, f_{IF}\, T}{2\,\Delta F}, \tag{7}$$

where

c = speed of light = 3×10^8 m/s,

f_{IF} = intermediate frequency (IF) at the output of the mixer (Hz), and
$T = 1/f_m$ = modulation period (s).

The modulation period of the 94 GHz radar is 1.6 ms, while ΔF is 230 MHz. The IF frequency band extends to 5 MHz. Therefore, the design range of this particular radar is 3.3 statute miles. This set of frequency parameters is not limiting with respect to range performance as the modulation period can be increased to extend the range at which target returns can be processed. The range resolution ΔR is

$$\Delta R = \frac{c}{2\,\Delta F} = 0.65 \text{ m.} \tag{8}$$

6. Radar architecture

The radar architecture is shown in Figure 5. The phase noise of the signal source is less than –90 dBc/Hz @ 10 kHz offset and less than –115 dBc/Hz @ 100 kHz offset. This performance is achieved by upconverting the frequency of a low phase noise source to 94 GHz. The directional coupler apportions the power between the output power amplifier and the mixer. The mixer configuration is homodyne since the same source is used to generate output power and the local oscillator signal. Separate antennas are used to transmit and receive to increase the isolation between the transmitted and received signals. Received power enters the receiver through a low noise amplifier, which reduces the noise figure of the receiver to less than 6 dB.

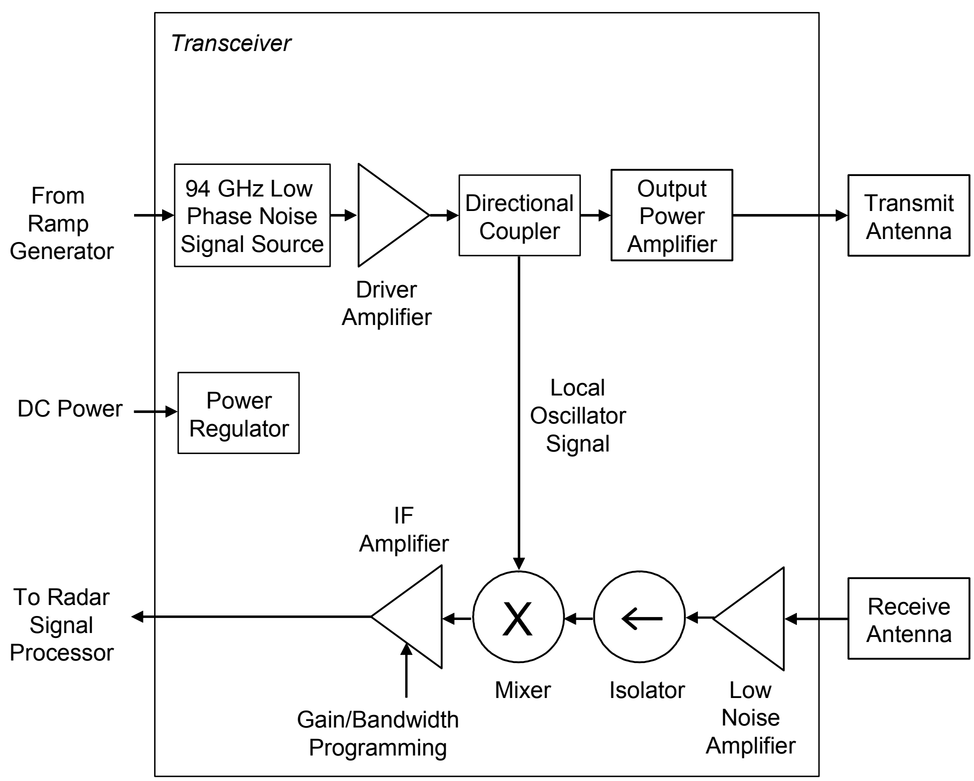

Figure 5. 94 GHz FMCW radar transceiver architecture using a low phase noise signal source and a receiver whose input is buffered with a low noise amplifier.

The radar signal processor is a PC containing auxiliary signal generation and signal processing cards. A ramp generator controlled through the PC bus provides the linear voltage sweep that generates the FMCW signal. A data acquisition card digitizes the IF signal and processes it using an FFT. The output of the FFT processing is normally displayed as backscattered amplitude in range versus azimuth angle or distance. Alternate displays of moving targets superimposed on GIS maps or two-dimensional visual perspective views of data are available.

7. 94 GHz radar bird detection data

The 575 mW 94 GHz radar was deployed at the Bolsa Chica Bird Reserve in Huntington Beach, CA in February and March 2004. Figure 6 depicts the birds flying over the reserve just before sunrise. Figure 7 shows the radar as it was setup in the parking lot powered by an automotive battery and DC-to-AC converter. Figure 8 contains a radar image of the birds flying overhead and the marsh features. Figure 9 is the corresponding radar image displaying only the moving bird targets. The numbers on the *y*-axis of the radar images give the range to the birds in meters. These ranges are not indicative of the detection limits of the radar, but rather of the targets (birds) of opportunity that were encountered.

Figure 6. Gulls and cormorants flying overhead at Bolsa Chica Bird Reserve, Huntington Beach, CA just before sunrise.

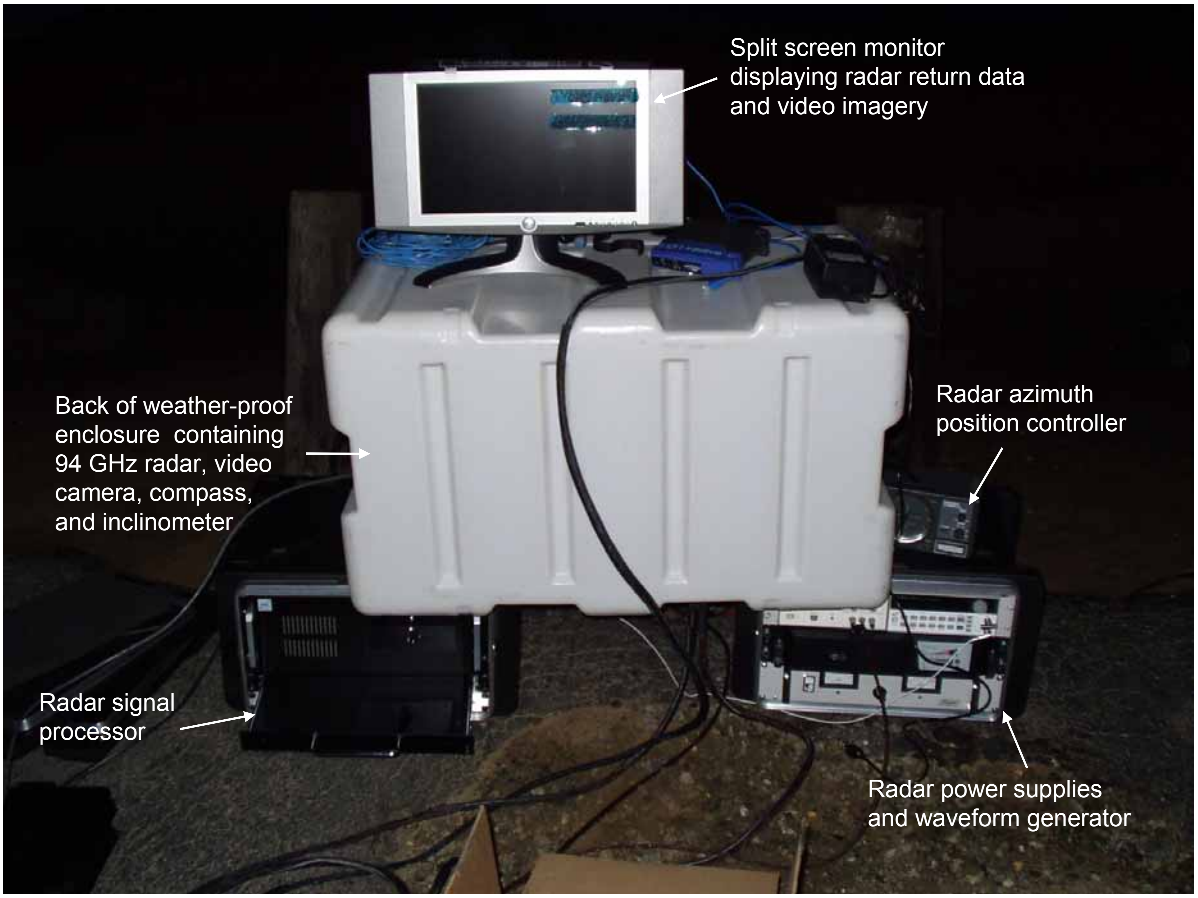

Figure 7. Radar as setup in parking lot at Bolsa Chica Bird Reserve.

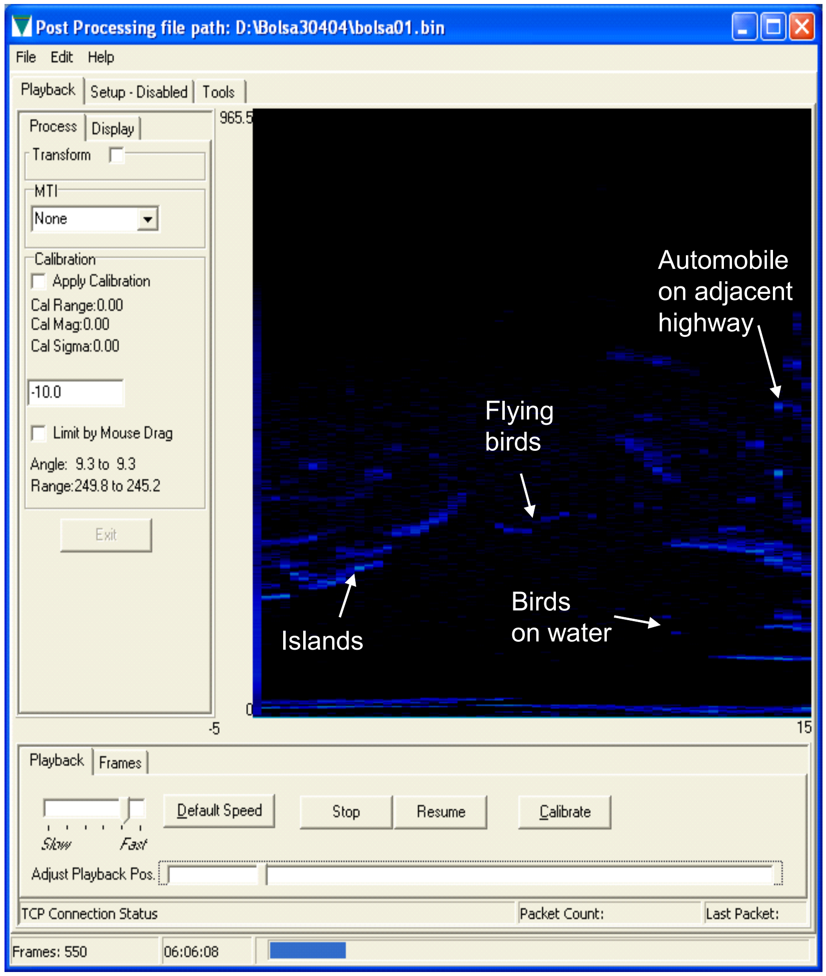

Figure 8. 94 GHz radar image of flying birds and stationary marsh features.

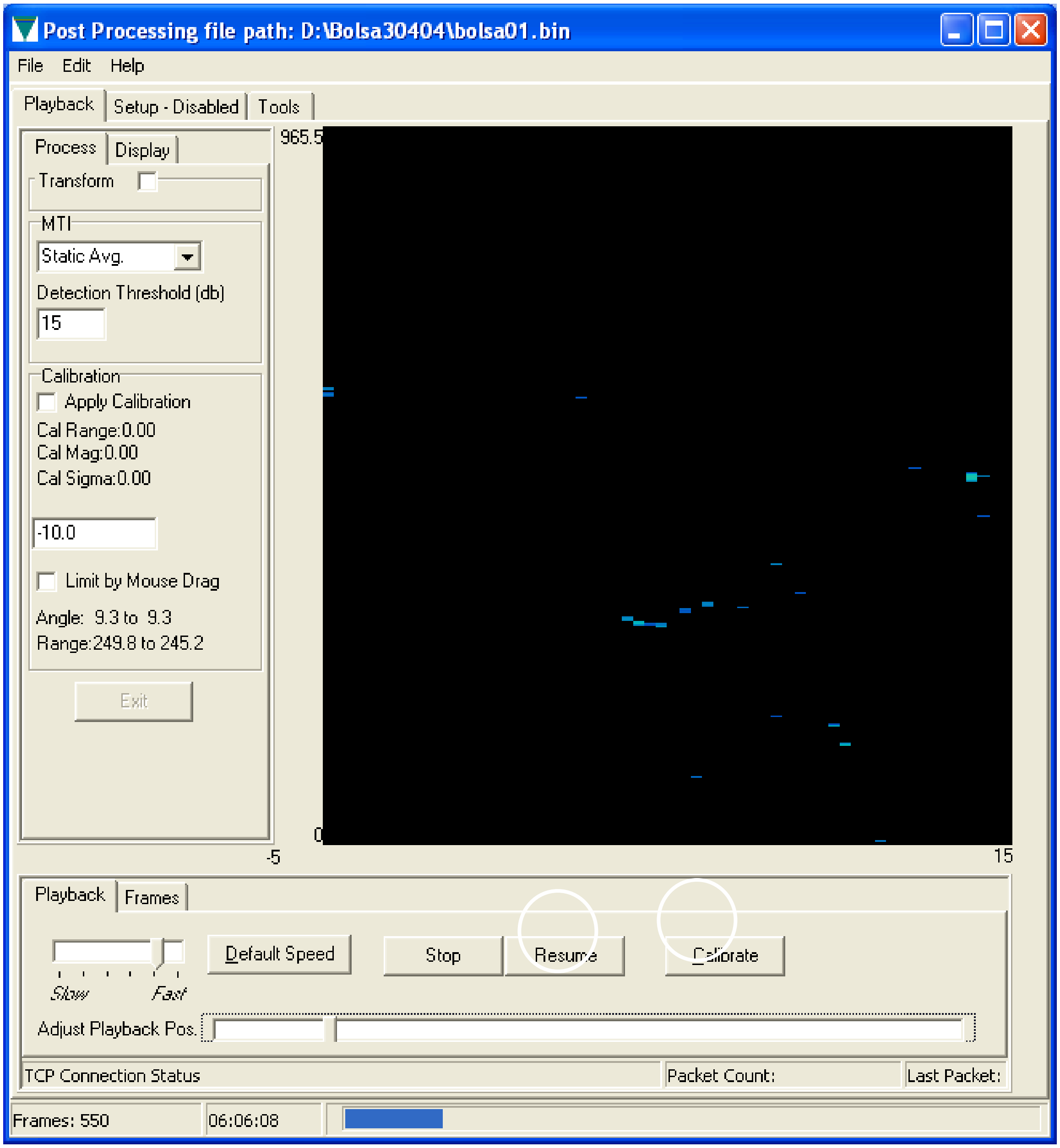

Figure 9. 94 GHz radar image of only moving bird targets. The stationary ground features are removed through signal processing.

8. Conclusions

The ability of a compact, light weight 94 GHz low noise, imaging radar to detect small and large birds has been demonstrated. The 575 mW output power source of this radar is modest, but appears sufficient to detect bird flocks at ranges up to 3 miles (4.8 km). Current solid state technology supports the manufacture of a 1 W CW 94 GHz power amplifier, which can be utilized to detect bird flocks at ranges up to 4 miles (6.4 km). Future plans call for deploying the radar at Dallas-Ft. Worth airport during Spring 2004 to evaluate its performance in an operational environment.

9. Acknowledgment

The authors gratefully acknowledge the assistance and insight of Robert Mino in assembling, testing, and gathering bird signature data with the imaging radar. They thank Jeff Paul and Tod Gentille for making available their expertise in radar design and signal processing algorithm development.